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Bibliometric analysis of biomaterial additive manufacturing for orthopedic applications: research trends and future research directions

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ABSTRACT

Advances in additive manufacturing have brought about significant changes in the development of biomaterials for orthopedic applications through the ability to produce implants and scaffolds with complex geometries, good mechanical properties, and the ability to be customized to patient needs. The rapid increase in the number of publications in this field has led to an ever-growing diversity of scientific information, necessitating a study capable of comprehensively mapping research trends. This study aims to analyze research trends regarding Additive Manufacturing of Biomaterials for Orthopedic Applications using a bibliometric approach. Data were obtained from the Scopus database through a search strategy employing a combination of relevant keywords. After filtering based on publication year (2020–2026), subject field (engineering, medicine), document type (articles), language (English), and keywords (biomaterials, 3D printing), 119 articles were selected as the research dataset. Next, the metadata was analyzed using the Biblioshiny software within the Bibliometrix package in R. The analysis included descriptive statistics, annual publication trends, author productivity, keyword co-occurrence networks, thematic evolution, and thematic maps. The results showed that the number of publications increased during the study period, with dominant themes including biomaterials, three-dimensional printing, and biocompatibility. The thematic evolution analysis revealed a shift in research from the development of basic biomaterials toward more specific applications, such as tissue engineering, patient-specific implants, and highly biocompatible biomaterials. This study provides a comprehensive overview of research developments and identifies potential directions for future research.

KATA KUNCI: bibliometric analysis; additive manufacturing; biomaterials; orthopedic applications; 3D printing.

1. INTRODUCTION

Advances in additive manufacturing (AM) have transformed the manufacturing paradigm in various fields, including the healthcare sector [1]. Unlike conventional subtractive manufacturing methods, AM technology builds objects incrementally by adding layers of material based on a three-dimensional digital model [2]. This approach enables the production of components with complex geometries and high precision, while also promoting efficient use of materials, making it one of the most promising technologies in the development of modern medical devices [3]. This capability is driving the use of additive manufacturing to produce medical devices tailored to each patient's anatomical needs [4].

In the field of orthopedics, additive manufacturing has been used to produce various types of implants, tissue scaffolds, fixation plates, and prostheses with designs that are more complex than those produced using conventional manufacturing methods [5]. This technology enables the formation of porous structures that resemble the architecture of natural bone, thereby enhancing osseointegration [6]. In addition, the porous structure can accelerate bone tissue regeneration while reducing the stress shielding phenomenon that often occurs with conventional metal implants [7], [8].

The success of additive manufacturing in orthopedic applications is greatly influenced by the characteristics of the biomaterials used. Biomaterials must have good biocompatibility, adequate mechanical properties, corrosion resistance, and the ability to interact safely with biological tissues [9]. Various studies have developed biomaterials based on metals, ceramics, polymers, and composite materials to improve the performance of orthopedic implants [3]. Titanium and its alloys remain the most widely used biomaterials because they possess high mechanical strength and excellent corrosion resistance [10]. On the other hand, hydroxyapatite, bioactive glass, and various polymer-based biomaterials continue to be developed to enhance the bioactivity of implant surfaces and accelerate the formation of new bone tissue [6], [11].

Current research on biomaterials focuses not only on the selection of specific materials, but also on the development of composite materials capable of combining the advantages of several types of biomaterials [12]. The integration of biomaterials with bioprinting technology enables the creation of scaffolds containing living cells, hydrogels, and growth factors, thereby opening up new opportunities in the field of tissue engineering [3]. This development shows that additive manufacturing is no longer merely a manufacturing technology, but has evolved into a platform for innovation in the development of next-generation biomaterials for orthopedic applications [13].

As interest in this technology has grown, the number of scientific publications on Additive Manufacturing of Biomaterials for Orthopedic Applications has increased significantly over the past few years [14], [15]. The published research covers the development of new materials, the optimization of printing parameters, the characterization of mechanical and biological properties, and clinical applications in various types of orthopedic implants [4]. Nevertheless, the increasing number of publications has led to scientific information becoming increasingly scattered, making it difficult to obtain a comprehensive overview of developments in this field of research. Therefore, a bibliometric approach is needed that can systematically map research trends, conceptual structures, and the direction of research development based on available scientific publications.

Problem Statement

Various studies have reported innovations in biomaterial development, optimization of printing process parameters, porous scaffold design, surface modification, and evaluation of mechanical and biological properties to improve the performance of orthopedic implants [5]. In addition, advances in 3D printing technology have driven the development of patient-specific implants, which allow for the creation of implants tailored to each patient's anatomical characteristics [4].

Nevertheless, the available research is still scattered across various disciplines with diverse focuses. Some studies place greater emphasis on the development of metallic biomaterials, while others focus on ceramic biomaterials, polymers, composite materials, and tissue engineering applications [16], [12], [11]. These differences in focus make it difficult to gain a comprehensive picture of research developments, the most dominant themes, the relationships among research topics, and emerging trends.

On the other hand, most publications still focus on experimental studies of specific materials or manufacturing processes, while research that charts the development of this field through a bibliometric approach remains relatively limited [13]. In fact, bibliometric analysis can provide objective information on publication trends, author productivity, the conceptual structure of research, relationships among keywords, and the evolution of research themes based on the metadata of scientific publications.

Based on these issues, this study is formulated into the following research questions.

a. What are the trends in publications on additive manufacturing of biomaterials for orthopedic applications during the 2020–2026 period?
b. Which authors have made the greatest contributions to this field of research?
c. What is the conceptual structure of the research based on the relationships between keywords (keyword co-occurrence network)?
d. How have research themes evolved based on thematic evolution and thematic map analyses?
e. Which research themes have developed well, and which still hold potential for future development?

Research Objectives

Based on the research problems that have been identified, this study aims to provide a comprehensive overview of research developments through a bibliometric analysis approach. Specifically, this study has the following objectives.

a. Analyze trends in scientific publications on additive manufacturing of biomaterials for orthopedic applications indexed in the Scopus database during the 2020–2026 period.
b. Identify the authors who have made the most significant contributions based on publication productivity.
c. Analyze the conceptual structure of the research through a keyword co-occurrence network to determine the relationships among research topics.
d. Identify the evolution of research themes using thematic evolution analysis.
e. Group research themes based on their level of development and relevance using a thematic map.
f. Identify well-developed themes and remaining research opportunities as a basis for future research recommendations.

The results of this study are expected to make an academic contribution in the form of a comprehensive scientific overview of the development of Additive Manufacturing of Biomaterials for Orthopedic Applications.

2. LITERATURE REVIEW

Additive Manufacturing in Orthopedic Applications

Additive manufacturing (AM), also known as three-dimensional (3D) printing, has evolved into one of the most innovative manufacturing technologies in the fields of engineering and biomedicine. This technology builds objects incrementally by adding layers of material based on a three-dimensional digital model, thereby enabling the production of components with complex shapes and a high degree of precision [16]. Compared to conventional subtractive manufacturing methods, additive manufacturing reduces material waste, speeds up the production process, and offers greater flexibility in product design [17].

In the field of healthcare, additive manufacturing has been applied to a variety of uses, such as the creation of anatomical models for surgical planning, prosthetics, medical devices, tissue engineering scaffolds, and orthopedic implants tailored to the patient's condition [1]. The ability to produce highly personalized products enables this technology to support the concept of patient-specific medicine, in which implant designs can be tailored based on medical imaging data, such as CT scans and MRIs [4].

One of the key advantages of additive manufacturing is its ability to produce porous structures that resemble the trabecular structure of natural bone [6]. These porous structures play a crucial role in enhancing cell infiltration, nutrient transport, and the formation of new bone tissue, thereby accelerating the osseointegration process following implantation [3]. In addition, controlling pore size, pore shape, and porosity allows for the adjustment of the scaffold's mechanical properties to more closely match those of natural bone and reduce the risk of stress shielding [5].

The growth of additive manufacturing is also driven by the increasing variety of printing technologies available. Fused Deposition Modeling (FDM) is the most widely used technology for polymer materials because its operating costs are relatively low and the process is simple [18]. For metallic biomaterials, technologies such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are the top choices because they can produce components with high density and good mechanical properties [10]. In addition, Selective Laser Sintering (SLS) and Stereolithography (SLA) are also widely used to produce scaffolds with high resolution and complex geometries [16]. The choice of technology is heavily influenced by the type of biomaterial, the desired product characteristics, and the requirements of the clinical application.

In addition to advances in printing technology, researchers are increasingly focusing on the integration of additive manufacturing with bioprinting approaches. This technology enables the printing of biomaterials combined with living cells, hydrogels, and growth factors to produce biological constructs that resemble native tissue. Several studies have reported the successful use of GelMA-based hydrogels, gelatin, and biodegradable polymers as printing media for scaffolds that support the proliferation and differentiation of bone cells. [19], [12]. These developments indicate that additive manufacturing is no longer merely a manufacturing technology but has evolved into a key platform in tissue engineering and regenerative medicine. These developments demonstrate that additive manufacturing plays a strategic role in supporting innovation in biomaterials and the development of orthopedic implants that are safer, more functional, and better suited to the needs of future patients [4], [11].

Biomaterials for Orthopedic Applications

Biomaterials are key components in the development of orthopedic devices because they serve as a medium that interacts directly with biological tissues to repair, replace, or support the function of damaged bone [9]. In orthopedic applications, biomaterials must meet various requirements, such as high biocompatibility, mechanical properties compatible with bone tissue, resistance to corrosion and wear, and the ability to support cell adhesion, proliferation, and differentiation [16].

Based on their characteristics, biomaterials for orthopedic applications are generally classified into four categories: metals, ceramics, polymers, and composite materials. Metallic biomaterials still dominate orthopedic applications because they offer high mechanical strength, resistance to cyclic loading, and long-term stability [10]. Titanium and its alloys, particularly Ti6Al4V, are the most widely used materials because they offer excellent corrosion resistance and high biocompatibility [11]. Various studies have also explored modifications to metal composition through the addition of bioactive elements and the optimization of printing parameters to enhance mechanical strength while improving the biological response to bone tissue [10]. Nevertheless, the high elastic modulus of metals compared to natural bone remains a challenge because it can lead to stress shielding; consequently, the development of porous structures has become a widely studied solution [5].

In addition to metallic biomaterials, ceramic biomaterials also play an important role in orthopedics because they can enhance bioactivity and accelerate the formation of new bone tissue. However, the brittle nature of ceramic biomaterials limits their use as structural materials subjected to high loads [16].

Polymer-based biomaterials have also seen rapid development, particularly in the fields of tissue engineering and biodegradable scaffolds [12]. Materials such as polycaprolactone (PCL), polylactic acid (PLA), polyether-ether-ketone (PEEK), and various types of hydrogels are being widely developed because they are easy to print using additive manufacturing technology [17]. In addition to having low density, some types of polymers are capable of undergoing gradual biodegradation, making them suitable for tissue regeneration applications [3]. Recent research also shows that PEEK-based scaffolds modified with bioactive materials can enhance osteoblast activity and accelerate the formation of new bone tissue [5].

Current research trends indicate an increasing use of composite materials that combine two or more types of biomaterials to achieve better characteristics than those of individual materials. Combinations of metals with bioactive glass, polymers with hydroxyapatite, and PLA-based scaffolds combined with hydrogels and silk fibroin have been reported to enhance mechanical properties while improving the biological response to bone tissue [12].

Overall, the development of biomaterials for orthopedic applications reflects a shift from the use of single materials toward multifunctional biomaterial systems designed to simultaneously meet mechanical, biological, and clinical requirements. The integration of biomaterials with additive manufacturing technology is one of the key factors driving innovation in the development of a new generation of orthopedic implants that are more personalized, safer, and have a higher potential for clinical success.

Current Research Trends

Research on additive manufacturing of biomaterials for orthopedic applications has shown significant growth in recent years. This growth has been driven by the need for manufacturing technologies capable of producing orthopedic implants with high precision, optimal mechanical properties, and good biocompatibility [4].

One of the most prominent trends in research is the development of porous scaffolds designed to mimic the structure of natural bone trabeculae [6]. In addition to scaffold design, recent research trends also indicate a growing focus on the development of composite biomaterials. Combinations of titanium with bioactive glass, PEEK with bioactive particles, and hydrogels combined with ceramic biomaterials have been reported to enhance cell adhesion, accelerate osteogenesis, and improve integration between the implant and bone tissue [20].

Advances in 3D bioprinting technology are also a topic that is attracting increasing attention. Unlike conventional additive manufacturing, bioprinting allows for the printing of biomaterials combined with living cells, hydrogels, or active biomolecules to produce biological structures that resemble natural tissues [3].

Another research trend is the increasing use of patient-specific implants designed based on medical imaging data, such as CT scans and MRIs [4]. This approach enables the creation of implants tailored to each patient's anatomy, thereby improving implant stability, reducing surgery time, and enhancing clinical outcomes. Advances in computer-aided design (CAD) software and 3D scanning technology are further accelerating the adoption of personalized approaches in orthopedics. Meanwhile, recent research is also beginning to integrate artificial intelligence (AI) and machine learning into both the design process and the optimization of additive manufacturing [15].

Although various innovations have been successfully developed, there are still a number of challenges that need to be addressed. Standardization of the printing process, consistent product quality, long-term validation of biomaterial performance, and the application of research findings to clinical practice remain the focus of future development [16]. Therefore, mapping research trends using a bibliometric approach is important for providing an overview of topics that have been well-developed and for identifying remaining research opportunities.

Research Gap

specific materials or technologies. For example, Dai et al. (2021) developed a scaffold based on Cu-doped bioactive glass to enhance bone regeneration, while Wu et al. (2024) evaluated a PEEK-based composite scaffold that demonstrated enhanced osteogenic activity. Other studies have focused on the development of hydrogels and composite biomaterials for tissue engineering applications [12]. On the other hand, Polozov et al. (2025) focused their research on the relationship between Selective Laser Melting (SLM) process parameters and the microstructural characteristics and mechanical properties of metallic biomaterials.

In addition to the development of biomaterials, research is also beginning to focus on the use of digital technology to produce patient-specific implants tailored to the patient's anatomy [4]. This approach indicates that research in additive manufacturing has evolved toward manufacturing systems that are more personalized, precise, and integrated with medical imaging technology.

Nevertheless, the results of the literature review indicate that these studies remain limited in scope, as they generally focus on only one type of biomaterial, one printing technology, or one specific orthopedic application. Information regarding the overall development of the research field, the relationships among research topics, the most influential authors, and the evolution of research themes has not yet been comprehensively documented. As a result, researchers face difficulties in identifying the direction of research development and determining which research opportunities remain open.

Table 1. Comparison of Previous Studies with Research Gaps

Authors	Research Focus	Key Findings	Limitations
Dai et al. (2021)	Bioactive glass scaffolds	Demonstrated enhanced bone regeneration using bioactive glass scaffolds.	Evaluated only a single type of biomaterial.
Allen et al. (2022)	Bioprinted hydrogel scaffolds	Reported that bioprinted hydrogel scaffolds support osteoblast proliferation.	Did not examine broader research trends in the field.
Ly et al. (2022)	Ceramic biomaterials	Reviewed the application of ceramic biomaterials for orthopedic tissue engineering.	Focused exclusively on a specific biomaterial category.
Rajput et al. (2023)	Silk fibroin composite scaffolds	Demonstrated improved biological performance of silk fibroin-based composite scaffolds.	Did not discuss the overall development and evolution of the research field.
Panda et al. (2024)	Additive manufacturing and artificial intelligence	Highlighted the potential of AI-assisted additive manufacturing for process optimization.	Did not perform a bibliometric analysis of the research landscape.
Suffo et al. (2024)	Personalized orthopedic implants	Discussed the development of patient-specific orthopedic implants.	Limited to hip prosthesis applications.
Wu et al. (2024)	PEEK composite scaffolds	Reported enhanced osteogenic activity of PEEK-based composite scaffolds.	Focused solely on PEEK-based biomaterials.
Polozov et al. (2025)	Selective Laser Melting	Investigated the optimization of mechanical properties of metallic biomaterials fabricated by Selective Laser Melting.	Did not analyze publication trends or research evolution.
This study	**Bibliometric Analysis of Additive Manufacturing of Biomaterials for Orthopedic Applications**	**Provides a comprehensive bibliometric analysis of publication trends, influential authors, conceptual structure, thematic evolution, and future research directions based on 119 Scopus-indexed articles published between 2020 and 2026.**	**Offers a comprehensive mapping of the research landscape to support future studies and identify emerging research opportunities.**

Furthermore, bibliometric studies on additive manufacturing of biomaterials for orthopedic applications remain limited. Most previous research has relied on systematic or narrative reviews, which do not quantitatively reveal the intellectual structure of the field. To address this gap, this study conducts a bibliometric analysis of 119 Scopus-indexed publications (2020–2026) using Biblioshiny. Unlike previous studies that focused on specific biomaterials or manufacturing technologies, this research comprehensively maps publication trends, influential authors, keyword co-occurrence, thematic evolution, and research themes to identify emerging directions in the field.

3. RESEARCH METHODOLOGY

Research Design

This study uses a bibliometric analysis approach to examine the development of research on Additive Manufacturing of Biomaterials for Orthopedic Applications. Bibliometric analysis is a quantitative method that utilizes the metadata of scientific publications to evaluate the development of a research field through indicators such as publication trends, author productivity, relationships between keywords, collaboration patterns, and the conceptual structure of a discipline [21]. This approach is widely used to provide an objective overview of scientific developments and to identify future research directions.

The study was conducted in several stages: literature identification, screening of articles based on inclusion criteria, metadata extraction, bibliometric analysis using the Biblioshiny software, and interpretation of the analysis results. All stages were carried out systematically to ensure that the data obtained were relevant to the study's objectives.

Data Collection

The research data were obtained from the Scopus database, which was selected for its extensive coverage of international journals and for providing comprehensive metadata that supports bibliometric analysis. The search strategy utilized a combination of Boolean operators (Figure 1) in the Title, Abstract, and Keywords fields with search terms related to additive manufacturing, biomaterials, and orthopedic applications. To identify relevant articles, a screening process was conducted using the criteria listed in Table 2.

Figure 1. Search strategy in the Scopus database

Table 2. Criteria and filters used

Kriteria	Filter
Database	Scopus
Publication Year	2020–2026
Document Type	Article
Language	English
Subject Area	Engineering, Materials Science, Medicine, Biomedical Engineering

Literature Screening Using PRISMA

The literature selection process was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines, as shown in Figure 2. This approach aims to ensure that the articles analyzed meet the established inclusion criteria, thereby yielding a relevant and high-quality dataset [22]. The selection process began with the identification of articles through the Scopus database using a predetermined search strategy. The articles were then filtered based on publication year, document type, language, and subject area. Articles that met all the criteria were subsequently used as the dataset for the bibliometric analysis.

In this study, the identification process yielded 660 documents from the Scopus database. After filtering based on the research criteria, 119 articles met all the requirements and were used in the bibliometric analysis phase using Biblioshiny.

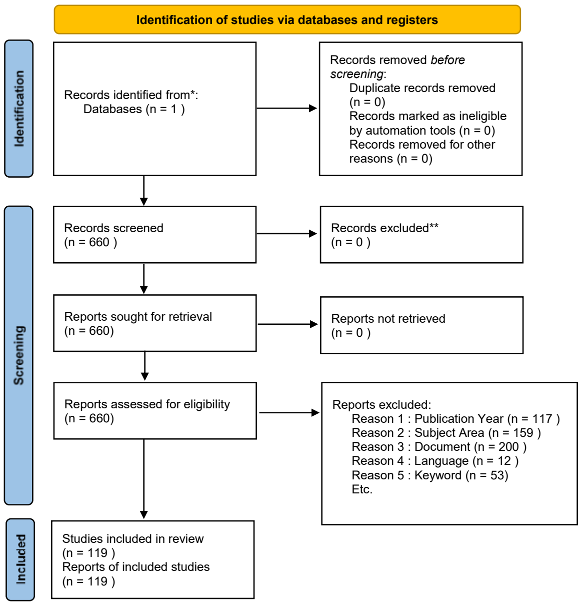

Figure 2. PRISMA 2020 flow diagram of article selection process.

Bibliometric Analysis

Article metadata obtained from Scopus was exported in CSV format and then analyzed using the Bibliometrix package via the Biblioshiny interface in the R software. Biblioshiny was chosen because it provides a variety of bibliometric analysis methods capable of illustrating research trends both quantitatively and visually. The analyses conducted in this study include:

a. Descriptive Analysis

Descriptive analysis is used to identify the general characteristics of the dataset, including:

- number of documents

- number of authors
- number of journals
- average citations
- publication growth rate
- author collaboration patterns

b. Annual Scientific Production

This analysis aims to illustrate the annual growth in the number of publications in order to identify research growth trends during the 2020–2026 period.

c. Most Relevant Authors

An analysis of author productivity was used to identify the authors who have made the greatest contributions based on the number of publications in this field of research.

d. Keyword Co-occurrence Network

Co-occurrence analysis is used to identify relationships among keywords that frequently appear together in publications, thereby illustrating the conceptual structure of the research.

e. Thematic Evolution

Thematic evolution analysis is used to identify changes in research focus over time based on the evolution of key terms.

f. Thematic Map

Thematic maps are used to group research themes based on centrality and density values, resulting in four thematic groups, namely:

- Motor Themes
- Basic Themes
- Niche Themes
- Emerging/Declining Themes

This analysis helps identify themes that have been well-developed as well as those that still offer opportunities for further research.

Research Workflow

The overall research process is shown in Figure 3.

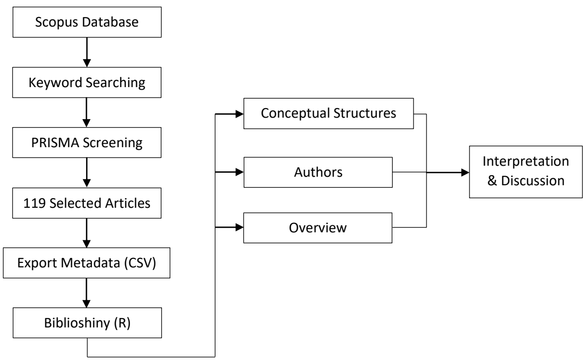

Figure 3. Research workflow

Research Framework

Research framework began with the collection of publication data from the Scopus database using a predetermined search strategy. Next, a literature selection process was conducted in accordance with the PRISMA guidelines to identify articles that met the research criteria. Metadata from the selected articles were then exported into CSV format and analyzed using Biblioshiny. The analysis results included descriptive statistics, publication trends, author productivity, keyword networks, thematic evolution, and thematic maps. All analysis results were then interpreted to describe the development of research on Biomaterial Additive Manufacturing for Orthopedic Applications and to identify future research directions.

4. RESULTS AND DISCUSSION

Descriptive Analysis of Publications

The bibliometric analysis in this study was conducted on 119 scientific articles obtained from the Scopus database using the search strategy described in Chapter 3. All articles were published between 2020 and 2026 and came from 67 publication sources (journals, books, and conference proceedings). The analyzed dataset had an Annual Growth Rate of 6.44%, indicating a relatively consistent increase in publications over the study period. Additionally, the average document age was 2.58 years, suggesting that most articles are recent publications and thus capable of representing the latest developments in the field of biomaterial additive manufacturing for orthopedic applications.

Overall, these 119 articles received an average of 35.14 citations per document, with a total of 7,373 references used as the basis for the research. The high average number of citations indicates that this field has garnered significant attention from the scientific community and has emerged as one of the most actively researched topics in biomedical engineering and additive manufacturing. In terms of document content, 1,822 Keywords Plus and 393 Author's Keywords were identified, reflecting the diversity of research topics ranging from biomaterial development, additive manufacturing process optimization, and porous scaffold design to patient-specific orthopedic implant applications.

The research collaboration also reveals interesting characteristics. The dataset consists of 693 authors, with only one article written by a single author, while the majority of articles were authored collaboratively. The "Co-authors per Document" value of 6.91 indicates that each publication involves an average of nearly seven researchers. Additionally, 31.93% of the publications resulted from international collaboration. These findings indicate that research on additive manufacturing of biomaterials is a multidisciplinary field that requires collaboration among researchers from various disciplines, such as mechanical engineering, materials engineering, biomedical engineering, medical science, and computational science. Cross-national collaboration also accelerates the exchange of knowledge, the development of new technologies, and the validation of biomaterial applications in clinical contexts.

The trend in the number of publications during the 2020–2026 period is shown in Figure 4. Based on the analysis, the number of articles published each year shows an upward trend. In 2020 and 2021, there were 11 articles each year, which then increased to 13 articles in 2022. A more significant increase occurred in 2023 and 2024, with 22 articles each year. Publication productivity peaked in 2025 with 24 articles, before declining to 16 articles in 2026.

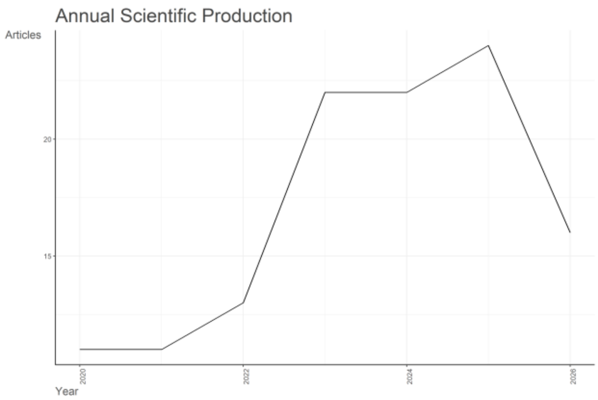

Figure 4. Annual scientific production (2020–2026). Created by authors through RStudio-Biblioshiny (2026)

The increase in the number of publications since 2022 indicates that research on additive manufacturing of biomaterials is gaining increasing attention from the scientific community. This trend is in line with the rapid advancement of additive manufacturing technology, which enables the production of orthopedic implants with complex geometries, high precision, and characteristics tailored to patients' needs [16]. In addition, advances in metal and polymer printing technologies, the increasing use of designs based on medical imaging (patient-specific implants), and the development of biomaterials with better mechanical and biological properties than conventional materials have also contributed to the increase in the number of publications [23]. Advances in computer-aided design (CAD) software, numerical simulation, and precision manufacturing technology have also contributed to accelerating innovation in this field [15].

The peak in publications in 2025 indicates that research on additive manufacturing of biomaterials has entered a more mature phase of development, marked by an increasingly diverse range of research focuses. Research is no longer limited to the development of metallic biomaterials but has also begun to focus on composite biomaterials, biodegradable materials, porous structures (lattice structures), surface modifications, and the integration of artificial intelligence technologies for implant design optimization [12], [19]. This shift in focus indicates that research is no longer limited to manufacturing processes but is also beginning to emphasize improvements in biological performance, the personalization of implants, and readiness for clinical implementation [3].

The decline in the number of articles in 2026 does not necessarily indicate a decrease in research interest. Given that 2026 is still an ongoing publication period, some articles may not have been fully indexed in the Scopus database at the time of data collection. Therefore, the number of publications for 2026 is expected to continue to increase as new articles are indexed. A similar phenomenon is often observed in bibliometric studies that use publication data from the current year, as the indexing process takes time before all articles are available in the database.

Overall, the upward trend in publications during the 2020–2026 period indicates that additive manufacturing of biomaterials for orthopedic applications is a rapidly growing field of research. This growth reflects the increasing demand for personalized implants, advancements in additive manufacturing technology, and progress in biomaterials capable of improving the success of orthopedic treatments. These findings serve as the foundation for further bibliometric analysis, which will identify the most productive authors, patterns of scientific collaboration, the conceptual structure of research, and the evolution of emerging themes in the field of Additive Manufacturing of Biomaterials for Orthopedic Applications.

Most Relevant Authors

An analysis of author productivity was conducted to identify the researchers who have made the greatest contributions to the field of additive manufacturing of biomaterials for orthopedic applications during the 2020–2026 period. Based on the results of a Biblioshiny analysis of 119 articles indexed in Scopus, 693 authors were identified as having contributed to scientific publications. This number indicates that research in this field is advancing through extensive collaboration and involves researchers from various disciplines, such as materials engineering, mechanical engineering, biomedical engineering, medicine, and biomaterials science.

Figure 5 shows a list of authors with the highest number of publications in the research dataset. The five most productive authors are Wang W, Wang Y, Zadpoor A.A., Zhao C, and Zhou C, each of whom produced five publications during the observation period. Meanwhile, several other authors, such as Chen J, Li D, Wang G, Wang L, and Zhang B, each contributed four publications.

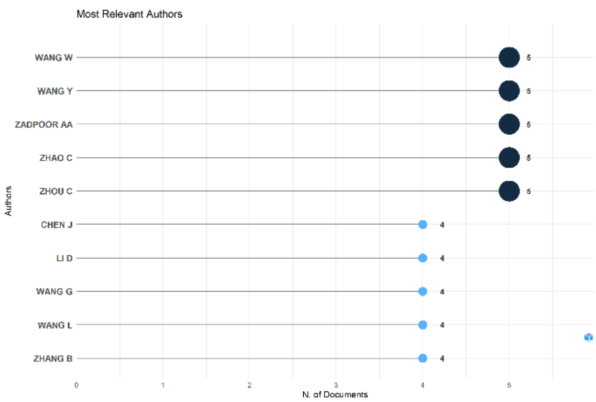

Figure 5. Most relevant authors. Created by authors through RStudio-Biblioshiny (2026)

These results indicate that research productivity in the field of biomaterial additive manufacturing is not dominated by a single author but is distributed among several research groups with relatively balanced levels of productivity. This situation indicates that this research field is advancing through the collective contributions of various institutions and research groups with different research focuses, such as the development of metallic biomaterials, bone tissue scaffolds, bioactive biomaterials, optimization of additive manufacturing parameters, and patient-specific orthopedic implant applications [5], [16]. This pattern of productivity demonstrates that research in additive manufacturing is multidisciplinary and involves collaboration among the fields of materials science, mechanical engineering, biomedical engineering, and medical science.

Interestingly, some researchers, such as Zadpoor A.A., are widely recognized in the fields of biomechanics and the design of porous (lattice) structures for orthopedic applications. Various studies published by this group have contributed to the development of porous scaffolds with mechanical properties that mimic those of natural bone, thereby enhancing osseointegration and reducing the stress shielding phenomenon [24]. Contributions like this from researchers demonstrate that the direction of research is not only focused on the development of new materials, but also on optimizing the structural design of biomaterials to improve the mechanical and biological performance of orthopedic implants [6]. On the other hand, the productivity of several authors with the last names Wang, Zhao, Zhou, Chen, and Li reflects the high level of research activity at institutions in Asia—particularly in China—which in recent years has become one of the centers for the development of additive manufacturing and biomaterials [25], [26], [27].

number of publications is the same as that of several other authors, his individual contribution to those articles is relatively greater. Conversely, the lower fractionalized values for other authors indicate that publications in this field are generally produced through team collaboration involving a significant number of authors. These findings suggest that research on biomaterial additive manufacturing is increasingly moving toward multidisciplinary collaboration involving experts in materials science, manufacturing, biology, and clinical practice to produce more comprehensive solutions.

Overall, the results of the authors' productivity analysis indicate that research on additive manufacturing of biomaterials for orthopedic applications is advancing through a broad network of collaborations, with relatively even contributions from various research groups. The absence of any single author exerting overwhelming dominance suggests that this field remains dynamic and open to a variety of research approaches.

Keyword Co-occurrence Network

A keyword co-occurrence network analysis was conducted to identify relationships among keywords that frequently appear together in publications on Biomaterial Additive Manufacturing for Orthopedic Applications. The network visualization in Figure 6 shows the conceptual structure of the research based on the interconnections among the topics discussed in the 119 articles analyzed. The larger the node size, the higher the frequency of a keyword's occurrence, while the connecting lines (edges) illustrate the strength of the relationship between keywords in the same publication.

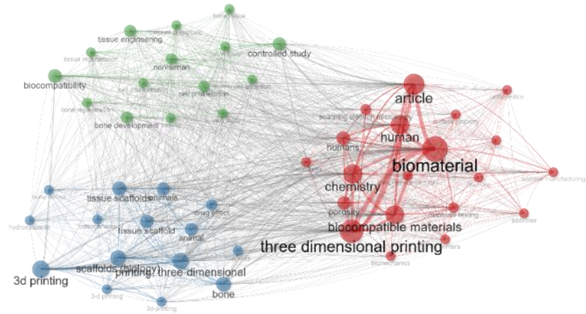

Figure 6. Co-occurrence Network. Created by authors through RStudio-Biblioshiny (2026)

Figure 6 shows that the research network is divided into three main clusters, each representing a different yet interrelated research focus. The red cluster is dominated by the keywords "biomaterials," "three-dimensional printing," "biocompatible materials," "chemistry," and "porosity." This cluster indicates that most research focuses on the development of biomaterials compatible with body tissues and the use of three-dimensional printing technology to produce implant structures with optimal mechanical and biological characteristics. The strong relationships among these keywords indicate that material design and manufacturing processes are two aspects that evolve in tandem within orthopedic research. This finding aligns with the study by Polozov et al. (2025), which showed that the microstructural characteristics and mechanical properties of biomaterials are significantly influenced by additive manufacturing process parameters.

The blue cluster centers on the keywords "tissue scaffolds," "scaffold," and several terms related to tissue engineering. This theme reflects growing attention toward the development of porous scaffolds as a medium for bone regeneration. The close interconnections among keywords in this cluster indicate that research is not only oriented toward tissue replacement but also toward the scaffold's ability to support cell adhesion, proliferation, tissue differentiation, and bone healing processes. Various studies report that pore design, pore size, and the porosity level of the scaffold have a significant influence on the success of osseointegration and the formation of new bone tissue.

Meanwhile, the green cluster is dominated by keywords related to biological evaluation, such as cell proliferation, biodegradation, controlled study, and in vitro study. This cluster reflects that biological evaluation is a critical stage following biomaterial development and the manufacturing process. Various studies not only assess the mechanical properties of biomaterials but also evaluate their biological responses to ensure the safety, biocompatibility, and effectiveness of the materials before they are applied in a clinical setting. This indicates that the success of a biomaterial is determined not only by its mechanical strength but also by its ability to support tissue regeneration without causing adverse biological responses.

Overall, the co-occurrence network indicates that research on biomaterials for additive manufacturing in orthopedic applications is advancing through the integration of three key aspects: biomaterial development, scaffold engineering for bone regeneration, and biological evaluation. The close relationships among the three clusters indicate that research in this field is multidisciplinary and leads to the development of implants that not only exhibit good mechanical performance but are also capable of optimally supporting tissue healing and regeneration. These findings are consistent with recent research trends that integrate materials science, tissue engineering, additive manufacturing, and digital technologies to produce more effective and personalized orthopedic solutions. [11], [15].

Thematic Evolution

A thematic evolution analysis was conducted to identify shifts in the focus of research on Additive Manufacturing of Biomaterials for Orthopedic Applications during the 2020–2026 period. The visualization in Figure 7 shows how research themes have evolved from the early period to the present based on the relationships among keywords appearing in the publications.

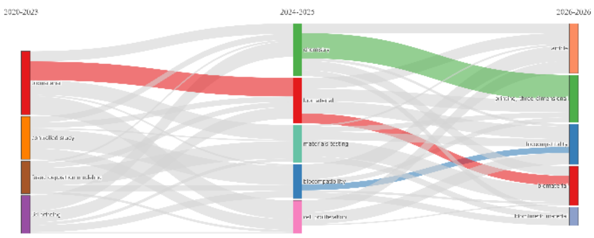

Figure 7. Thematic Evolution. Created by authors through RStudio-Biblioshiny (2026)

During the 2020–2023 period, research was dominated by the themes of biomaterials, controlled studies, fused deposition modeling (FDM), and 3D printing. These themes indicate that early-stage research remains focused on material development, the application of additive manufacturing technologies, and initial validation through experimental studies. The presence of fused deposition modeling (FDM) as one of the main themes indicates that extrusion-based printing technology remains a widely used method in the development of scaffolds and biomaterial prototypes for orthopedic applications due to its relatively low cost, ease of fabrication, and compatibility with various types of polymer biomaterials. The dominance of these themes indicates that the research focus during the early period was still directed toward proof of concept and the development of viable manufacturing methods for biomedical applications.

Entering the 2024–2025 period, there was a shift in research focus toward more specific themes, namely chemistry, materials testing, biocompatibility, and cell proliferation, while the theme of biomaterials remained the primary link between periods. This shift indicates that research is no longer solely oriented toward fabrication processes but is also beginning to emphasize material characterization, evaluation of mechanical properties, and biological responses to the developed biomaterials. The increased attention to biocompatibility and cell proliferation demonstrates that the success of biomaterials is determined not only by their mechanical performance but also by their ability to support cell adhesion, proliferation, and differentiation—key prerequisites for successful bone tissue regeneration. Consequently, the direction of research is evolving toward improving the quality, safety, and effectiveness of biomaterials before their clinical application.

By 2026, the evolution of research themes indicates that the keywords "printing," "three-dimensional," "biocompatibility," and "biomaterials" will dominate, while the theme of chemistry will continue to be strongly linked to advancements in 3D printing technology. This suggests that current research is beginning to integrate the optimization of additive manufacturing processes with the development of biomaterials that exhibit high biocompatibility. [4]. In addition, the emergence of biomimetic materials indicates a growing focus on developing materials capable of mimicking the structure, composition, and function of natural bone tissue, thereby enhancing osseointegration and tissue regeneration. This trend suggests that research has shifted from simply producing printable implants to the development of smart biomaterials capable of actively interacting with biological environments.

Overall, the results of the thematic evolution analysis indicate a gradual progression in research, beginning with the development of printing technologies and basic biomaterials, continuing with material characterization and biological evaluation, and ultimately leading to the development of biomimetic biomaterials and personalized implants. This evolution reflects the growing maturity of the field of Additive Manufacturing of Biomaterials for Orthopedic Applications, which now focuses not only on manufacturing aspects but also integrates materials science, tissue engineering, and digital technology to produce more effective orthopedic solutions tailored to clinical needs.

Thematic Map

A thematic map analysis was conducted to identify the level of development and relevance of research themes based on two parameters. Based on these two parameters, the research themes were grouped into four quadrants: Motor Themes, Basic Themes, Niche Themes, and Emerging/Declining Themes, as shown in Figure 8.

In the Motor Themes quadrant (top right), the themes of biocompatibility, controlled studies, and tissue engineering have high centrality and density values. This positioning suggests that these themes have developed well and play a significant role in the overall research structure. This indicates that research on the biocompatibility of biomaterials and tissue engineering has become a primary focus in the development of additive manufacturing-based biomaterials.

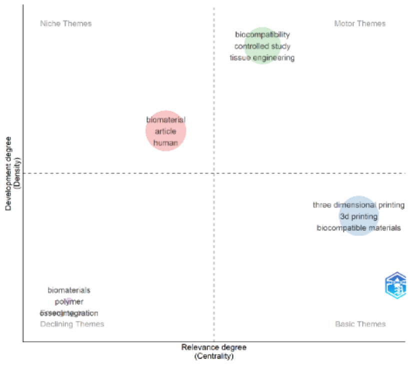

Figure 8. Thematic Map. Created by authors through RStudio-Biblioshiny (2026)

The Basic Themes quadrant (bottom right) is dominated by three-dimensional printing, 3D printing, and biocompatible materials. These themes exhibit a high degree of interconnection with various research areas, but their level of internal development remains relatively lower compared to the Motor Themes. This suggests that 3D printing technology serves as the primary foundation for orthopedic biomaterials research and forms the basis for various further developments, including process parameter optimization, scaffold design, and the fabrication of personalized implants.

In the Niche Themes quadrant (top left) are the themes biomaterials, human, and article. Themes in this quadrant exhibit a fairly high level of internal development, but their interconnections with other themes are relatively lower. The presence of the keyword “human” indicates that some research has focused on application or clinical evaluation aspects, including the development of patient-specific implants and the assessment of biomaterial performance in biological environments.

Meanwhile, the Emerging/Declining Themes quadrant (bottom left) contains the themes “biomaterials,” “polymer,” and “osseointegration.” This position indicates that these themes have relatively low levels of interconnectivity and development within the analyzed dataset. This condition does not necessarily mean that the themes have been abandoned, but it may indicate that the research focus has shifted toward more specific topics, such as biocompatibility, tissue engineering, and three-dimensional printing.

Overall, the thematic map shows that research developments regarding additive manufacturing of biomaterials for orthopedic applications are moving toward the integration of three-dimensional printing technology, biocompatibility, and tissue engineering. These three themes form the primary foundation for the development of next-generation biomaterials that not only meet mechanical requirements but are also capable of supporting tissue regeneration and improving implantation success. These findings align with the results of the co-occurrence network and thematic evolution analyses, which show that research is increasingly focused on the development of biomaterials that are functional, safe, and tailored to clinical needs.

Discussion and Future Research Directions

The results of the bibliometric analysis show that research on Additive Manufacturing of Biomaterials for Orthopedic Applications has seen significant growth during the 2020–2026 period. The annual increase in the number of publications reflects the scientific community’s growing interest in the use of additive manufacturing technology in the development of biomaterials for orthopedic applications. Advances in 3D printing technology enable the production of implants with complex shapes, controlled porous structures, and characteristics that can be tailored to a patient’s anatomy (patient-specific implants). These factors make additive manufacturing one of the most promising technologies in the development of modern biomaterials.

An analysis of author productivity indicates that research in this field is advancing through multidisciplinary and international collaboration. No single research group dominates the field, so innovations originate from various institutions with different research focuses. This pattern of collaboration indicates that the development of biomaterials for orthopedic applications requires not only expertise in materials and manufacturing but also involves aspects of biology, medicine, biomechanics, and tissue engineering. This multidisciplinary nature is one of the factors accelerating technological development and expanding the scope of research.

The results of the keyword co-occurrence network show that current research centers on three main groups: biomaterial development, 3D printing technology, and scaffold engineering for tissue regeneration. These three groups are closely interrelated, indicating that research no longer focuses on the development of materials in isolation but integrates structural design, mechanical characterization, and biological evaluation into a single biomaterial development system. This integration is one of the key characteristics of modern biomaterials research for orthopedic applications.

Thematic evolution analysis reveals a shift in research focus from manufacturing aspects toward biological evaluation and clinical applications. In the early period, research primarily addressed 3D printing and fused deposition modeling technologies, whereas in the subsequent period, attention shifted to materials testing, biocompatibility, and cell proliferation. This shift indicates that research has entered a more mature stage, where the success of biomaterials is measured not only by fabrication capabilities but also by biological performance and their potential for clinical implementation.

These findings are reinforced by the results of the thematic map, which identifies biocompatibility, controlled studies, and tissue engineering as “Motor Themes.” This positioning indicates that current research is increasingly focused on developing biomaterials that are safe, capable of supporting tissue regeneration, and have the potential for translation into medical applications. On the other hand, three-dimensional printing and biocompatible materials remain in the “Basic Themes” category, indicating that additive manufacturing technology remains the primary foundation for future research developments. This suggests that although 3D printing technology has advanced rapidly, there are still many opportunities to improve the quality of the manufacturing process, dimensional accuracy, mechanical properties, and biological performance of the resulting products.

Based on the overall results of the analysis, there are several research opportunities that remain open. First, research on composite materials that combine metals, ceramics, and polymers is expected to continue evolving to achieve a balance between mechanical strength, corrosion resistance, and biocompatibility. Second, the integration of biomimetic materials with additive manufacturing technology has the potential to produce scaffolds that more closely resemble natural bone structures, thereby enhancing the osseointegration process. Third, the application of artificial intelligence (AI)-based design and computational optimization is expected to become a new research direction for producing more efficient scaffold designs tailored to patient needs. Additionally, developments in 4D printing, smart biomaterials, and materials capable of responding to changes in the biological environment are also topics expected to be increasingly studied in the coming years.

Nevertheless, this study has several limitations. The bibliometric analysis relied solely on articles from the Scopus database covering the period 2020–2026; thus, publications from other databases such as Web of Science, PubMed, or Dimensions were not included. Furthermore, the analysis results were significantly influenced by the available metadata, including variations in keyword and author name spelling. Therefore, future research is recommended to combine multiple databases, perform more in-depth keyword normalization, and compare the bibliometric results with a Systematic Literature Review (SLR) to obtain a more comprehensive picture of the development of additive manufacturing-based biomaterials for orthopedic applications.

Overall, the results of this study indicate that the field of Additive Manufacturing of Biomaterials for Orthopedic Applications remains in a phase of strong growth and continues to evolve toward the development of smarter, more biocompatible, and patient-centered biomaterials. The integration of additive manufacturing technology, materials science, and tissue engineering is expected to be a key driver of innovation in the coming decade. Therefore, these bibliometric results not only provide an overview of the current state of research but can also serve as a reference for researchers in selecting topics, establishing collaborations, and identifying research opportunities with high scientific and clinical impact.

5. CONCLUSION

This study aims to analyze the development of research on Additive Manufacturing of Biomaterials for Orthopedic Applications through a bibliometric approach to 119 articles indexed in the Scopus database during the 2020–2026 period. The analysis was conducted using Biblioshiny software to identify publication trends, author productivity, relationships among keywords, the evolution of themes, and the thematic structure of the research.

The results show that the number of publications has increased at a relatively consistent annual growth rate of 6.44%, indicating growing attention from the scientific community toward the use of additive manufacturing technology in the development of orthopedic biomaterials. Research in this field is also multidisciplinary, as reflected by the high number of authors involved and strong international collaboration in generating innovations in the fields of biomaterials, tissue engineering, and additive manufacturing technology.

An analysis of keyword co-occurrence revealed that the research is dominated by three main focuses: biomaterial development, three-dimensional printing technology, and tissue engineering. These three themes are closely interrelated and indicate that research is not only focused on fabrication processes but also on improving mechanical properties, biocompatibility, and tissue regeneration capabilities. Furthermore, the results of the thematic evolution analysis show a shift in research focus from the development of manufacturing technologies toward biological evaluation and clinical applications. These findings are reinforced by the thematic map, which identifies biocompatibility, controlled studies, and tissue engineering as driving themes, while 3D printing and biocompatible materials serve as foundational themes underpinning future research development.

This study provides a comprehensive overview of the direction of research in additive manufacturing of biomaterials for orthopedic applications and identifies both established themes and those with potential for further development. The analysis results indicate that future research is expected to increasingly focus on the development of biomimetic biomaterials, composite materials, personalized implant designs, and the integration of artificial intelligence into the design and optimization processes of additive manufacturing. Therefore, the results of this study are expected to serve as a reference for academics, researchers, and practitioners in understanding the research landscape and determining the future direction of biomaterial technology development for orthopedic applications.

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